CHARACTERIZING NEAR-SURFACE KARST SYSTEM UNDER THREE STORMWATER RETENTION BASINS IN SILVER SPRINGS, FLORIDA

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Abstract

Water resources in karst systems are particularly vulnerable to contamination by polluted surface water, such as stormwater runoff, due to their specific geologic and hydrogeological characteristics. Better understanding of near-surface karst systems may inform contaminant transport and protective management of karst aquifers and springs. Ground penetrating radar (GPR) and electromagnetic (EM) geophysical data were collected in three stormwater retention basins within the Silver Springs springshed in Florida to investigate configuration of the near-surface karst system. The reported sinkhole data indicated 14 sinkhole occurrences with diameter ranging from 0.6 to 6 m in Basin 1, 11 sinkholes with diameter ranging from 0.6 to 3 m in Basin 2, and no sinkholes in Basin 3. Several sinkholes were identified by visual field survey, including a 2-m diameter sinkhole in Basin 2 that connected stormwater runoff directly with the surficial aquifer. GPR (270 MHz with 110 to 150 nanosecond time ranges) was accomplished in 3 m perpendicular transects, with penetration depth of 6 to 6.7 m. EM34-3 was applied with 10-m intercoil spacing in vertical and horizontal coplanar modes. 1.5% of survey area in Basin 1 is covered by surface sinkholes, while 2.5% of the area is covered by detected subsurface

karst anomalies. An overall correlation can be observed between surface and subsurface features in Basin 1. Low conductivity EM zones in the vertical (rather than horizontal) coplanar are correlated fairly well with the detected GPR anomalies. Surface sinkholes consist approximately 0.4% of survey area in Basin 2 while no considerable subsurface anomaly was detected by GPR, suggesting no correlation between surface and shallow karst system. The spatial variation of EM response in the vertical coplanar is relatively correlated with the spatial distribution of sinkholes in Basin 2. Though surface sinkhole was not recorded or observed in Basin 3, approximately 11% of the survey area is covered by subsurface anomalies. The near-surface karst system in the study area is highly heterogeneous, indicating that transport rates and contaminant transformations in the subsurface are likely to be similarly heterogeneous.

Introduction

Stormwater management in karst regions requires adequate understanding of contaminant transport within karst aquifers. Regions of karst geology may contain sinkholes, sinking streams, subsurface voids, and springs. Land surface, vadose soil layers, and aquifers may be characterized by high heterogeneity and anisot-

ropy of hydraulic conditions, resulting from dissolution processes in carbonate rocks (Ford and Williams, 2013; Shokri et al., 2016; Moore and Beck, 2018). Karst aquifers are typically susceptible to contamination due to the potential direct connections from contaminated surface water to groundwater with little or no attenuation by soil (Bonneau et al., 2017; Moore and Beck, 2018). Non-point sources of nutrient and contaminants delivering from roadways and urban areas can be a major source of groundwater pollution (Bouchard et al., 1992; Pitt et al., 1999; Mallin et al., 2009; Suthar et al., 2009; Eller and Katz, 2017).

For instance, stormwater management with dry and wet retention basins in karst areas of Florida requires particular attention since substantial volumes of surface runoff infiltrate in such retention basins. In addition to infiltrating stormwater runoff as their primary functions which provide drainage for roadways and urban areas, stormwater retention basins are designed for treating contamination through physical, chemical, and biological activities in their upper layer of soil (Harper and Baker, 2007). However, their performance can negatively be influenced by configuration of bottom of basins as concentrated water may flow through subsurface karst features. Degrading water quality in Florida's lakes, rivers, and springs such as Silver Springs in Central Florida has received widespread attention due to excess non-point nutrient pollution (Heffernan et al., 2010; Hicks and Holland, 2012; Liao et al., 2019). Proactive techniques to characterize contaminant transport in karst systems and design protective measures against aquifer contamination are necessary in karst regions. Thus, particular attention is needed with respect to configuration of near-surface karst systems in the vicinity of water retention basins.

Non-intrusive surface geophysical techniques such as ground penetrating radar (GPR) and frequency-domain electromagnetic terrain conductivity meter (EM) have been utilized for characterizing near-surface karst features. For instance, GPR and EM have been used to detect caverns, sinkholes, conduits and structural discontinuities, and preferential flow paths of percolating water in karst systems (Militzer et al., 1979; Smith, 1986; Ahmed and Carpenter, 2003; Jardani et al., 2007; Zhu et al., 2011; Chalikakis et al., 2011; Fernandes et al., 2015; Sevil et al., 2017). The combination of GPR and EM techniques have been utilized for characterizing

near-surface conditions in karst areas (Doolittle and Collins, 1998).

GPR can typically provide high-resolution images for near-surface investigations (Chalikakis et al., 2011). However, the EM34-3 allows for various exploration depths by applying different intercoil spacing (10, 20, or 40 m) and two dipole modes of data collections (horizontal and vertical) (McNeill, 1980). The principal of EM technique is based on a set of transmitter and receiver coils within which electrical current is generated. A primary transmitter coil is set to a discrete frequency and a secondary magnetic field is generated depending upon the conductivity of subsurface media (Chalikakis et al., 2011). The electrical conductivity of media is related to mineralogy, porosity, pore water conductivity, and degree of saturation.

The objective of this research is to characterize near-surface karst feature anomalies using GPR and EM techniques in three stormwater retention basins located within the springshed of a high-magnitude freshwater spring (Silver Springs) in Florida. This geophysical research can provide important information about near-surface karst condition in the area to local municipalities and organizations aimed at protecting water quality.

Study Area and Geological Setting

The study area is comprised of three water retention basins (Basin 1, Basin 2, and Basin 3) located near the city of Ocala in Marion County, Florida (Figure 1). These study basins are located in the springshed of Silver Springs (2,362 km²), a first-magnitude freshwater spring supplied by the Upper Floridan Aquifer (UFA) (Figure 1).

Hydrogeologically, an unconfined surficial aquifer (Pliocene to Holocene) consisting of sand, silty sand, to clay sediments overlays a semi-confining unit of interbedded quartz, sand, silt, and clay of Hawthorn Group (Miocene) (Knowles et al., 2002; Phelps, 2004). The semi-confining unit separates the surficial aquifer from the UFA which forms by limestone to fossiliferous sandy limestone of Suwanne Limestone (Oligocen) and white to creamy granular limestone and dolomite formation of Ocala Limestone (Upper Eocene) (Knowles et al., 2002; Phelps, 2004). The surficial aquifer has varied thickness and is typically absent in the area where carbonate rocks are exposed (Phelps, 2004; Knowles, 1996).

Figure 1. Silver Springs springshed in Florida (A, dotted polygon), stormwater retention basins investigated with respect to Silver Springs (B) with including reported sinkholes. Sinkhole data is from Florida Department of Transportation. Note: solid green color lines present border of the basins while light dotted green color lines indicate the geophysical coverage area within the basins.

Geomorphologically, the springshed is low-gradient (55 m of relief), and the lowest elevation corresponds to the location of main Silver Springs vents, forming a local base level for groundwater.

Closest to the springshed divide at elevation of 17 m a.m.s.l., Basin 1 (1.56 ha) is rectangular with dimensions of approximately 182 m by 85 m and 4700 m distance from Silver Springs (Figure 1). Basin 2 (2.45 ha, located approximately 3400 m from Silver Springs) is semi-trapezoidal with basin elevation of 13.4 m a.m.s.l., about 4.5 to 6 m lower than the adjacent roads. Closest to Silver Springs (550 m), Basin 3 (0.22 ha) is semicircle (approximately 61 m by 37 m) with basin elevation of 13 m a.m.s.l. The storm water basins were dry during data collection, however, some parts in the middle of Basin 1 and Basin 2 could hold water for two or three days after heavy rainfalls. The basins were covered with sparse vegetation which were mowed before surveying.

Methods

A GSSI GPR SIR 3000 system and a Geonics EM34-3 were used at the three study basins. The GPR data was

collected on 3-m grids across each site with 270 MHz of frequency of antenna (512 samples per scan) and time range of 150 (Basin 1) and 110 nanoseconds (Basin 2 and Basin 3) in 16-bit data formats. The collected data provided depth investigations of 6 to 6.7 m. EM data were collected using 10-m intercoil spacing with 6 m spacing between the stations and frequency of 6.4 kHz (maximum accuracy of 0.1 millimhos/m) in vertical coplanar (horizontal dipole) and horizontal coplanar (vertical dipole) modes, providing an effective exploration range of 7.5 m and 15 m, respectively (McNeill, 1980).

GPR data were processed with Radan 7. The air-ground contact which is referred as the distance between the ground surface and receiver and usually reflects in the data was removed for providing more accurate estimation of the depth to the reflectors. A dielectric constant of 6, appropriate for semi-saturated sandy sediments in Florida, which is associated to velocity of pulses and thus estimation depth, was chosen for the analysis. The location of the anomalies identified in the GPR data were transferred on to scaled field maps and then digitized for

further interpretations. The anomalies were categorized in terms of apparent level of severity into severe level (level A) and less severe (level B) anomalies. This level of severity was based upon two parameters: (1) the localized increased in the penetration depth of the GPR signal relative to the surrounding (non-anomaly) area and (2) the increase in amplitude of the GPR signal at depth within the anomaly area in comparison to the surrounding non-anomaly areas. Considering the dimension of the surface sinkholes (reported and observed) and detected subsurface features, spatial statistical calculations with respect to survey area at each basin were calculated. The EM data were used for generating spatial variation of conductivity in the basins. The contour maps of con-

ductivity measurements were created using a kriging method and inspected in combined with the prepared GPR maps.

Results and Discussion

Basin 1

Field observations indicated open sinkholes in Basin 1. In total, 14 sinkholes were recorded in Basin 1, with estimated area of about 245 m². A large (approximately 3 m diameter) collapsed sinkhole was observed in the northeast part of Basin 1, near the stormwater inlet (Figure 2A). A small, deep (approximately 1 m) soil pipe was observed in southeast part of Basin 1 (Figure 2B). Sixty-four subsurface features were detected by GPR at depths

Figure 2. (A) Collapsed sinkhole near stormwater inlet pipe in Basin 1, (B) small deep soil pipe in Basin 1, (C) partially-collapsed pits in Basin 2 and (D) open sinkhole in Basin 2. Note: surface water runoff was directly discharging into local surficial aquifer in an open sinkhole in Basin 2.

ranging from 0.6 to 6 m (Table 1), categorized as 7 level-A anomalies and 11 level-B anomalies (Table 1 and Figure 3A and 3B). The ratio of the area of surface features to the survey area in Basin 1 is relatively similar to that for detected near-subsurface features (Table 1). The correlation of the EM horizontal dipole contour map is a better fit with detected GPR anomalies than the vertical dipole (Figure 3A and 3B). Such result is likely related to the comparatively same depths of survey in the horizontal dipole mode of EM data collection (approximately 7.5 m) with the GPR (6 to 6.5 m) technique than that in vertical dipole mode of data collection (approximately 15 m) (McNeill, 1980).

There is relatively good corroboration between various techniques of detecting potential near-surface karst features in Basin 1. For example, observed good correlation between low conductivity areas (red-colored areas in the middle-west and southeast parts of the basin) and high conductivity areas in the northeast part of the basin (blue areas) (Figure 3A and 3B). Low conductivity areas are associated with presence of media with low clay content (Kovalevsky et al., 2004). Occurrence of several level-A anomalies detected by the GPR within the low conductivity EM zones in the middle-west and southeast of the basin may confirm this result (Figure 3A and 3B). The high-conductivity anomaly in the northeast part of Basin 1 (Figure 3A) corresponds to the location of the collapsed sinkhole shown in Figure 2A. That high-

conductivity area may be associated with a filled sinkhole as a conductive zone or an enhanced moisture zone (Ahmed and Carpenter, 2003). The location of the collapsed sinkhole, near the drainage pipe system, may be characterized by higher moisture content than the rest of the basin. In addition, a good correlation can be observed between reported sinkholes and detected uncategorized GPR anomalies in this basin (Figure 4).

Basin 2

Eleven sinkholes and partially-collapsed pits were reported/observed in Basin 2 (Figure 1 and Figure 2C and 2D). At least three sinkholes were observed in the north and west edge of Basin 2 during visual field survey. It was likely that the observed sinkholes were associated with reported sinkholes in the basin (Figure 1). The open sinkholes were directly connected to the surficial aquifer, allowing contaminated surface runoff to directly discharge into the aquifer (Figure 2D). Despite the fact of observed surface sinkholes and many reported sinkholes in Basin 2, GPR detected only one subsurface feature with the depth of about 2.3 m and area of 2.5 m² (Table 1 and Figure 4). The location of the detected subsurface feature was near (~5 m) the observed open sinkhole (Figure 2D). Despite GPR data, EM contour maps suggested a relatively good correlation between low conductivity regions and locations of observed sinkholes (Figure 3 and Figure 1). Although sensitivity to geologic anomalies are higher in vertical dipole mode of EM data

Table 1. Characteristics of surface and near-surface detected features in the surveyed area of the basins.

Basin	Feature	Number of Features	Feature area (m ²)					Depth range (m)	Survey area (ha)	% total area of feature to survey area of basin
			Min	Max	Mean	STD	Total			
1	S	14	0.3	118.2	101.2	31.4	245.6	0.6 - 6	1.56	1.5
	N-S	64	0.4	46.1	19.5	15.1	400.3	0.5 - 6.7		2.5
2	S	11	0.1	14.3	2.5	4.4	27.9	0.6 - 3	1.44	0.4
	N-S	1	NA	NA	NA	NA	2.5	2.3		1.7×10 ⁻³
3	S	NA	NA	NA	NA	NA	NA	NA	0.13	NA
	N-S	53	0.4	31.7	2.6	4.6	137.5	0.3 to 6		10.9

Note: Under feature column, S indicates surface feature and N-S indicates near-surface features. Surface features include reported data by Florida Department of Transportation. Feature area is the area associated to the features. Survey area is the area within the basin which was surveyed by GPR and EM techniques.

Figure 3. Variation in EM horizontal and vertical dipoles and GPR anomalies in Basin 1 (A and B), Basin 2 (C and D), and Basin 3 (E and F). The intercoil spacing in EM survey was 10 m. Note: Depth of investigation in EM horizontal dipole is approximately 7.5 m while that is approximately 15 m in vertical dipole mode. The depth of GPR anomalies in each pair map are same.

(Nobes, 1999; Caminha-Maciel and Figueiredo, 2013), a better correlation can be observed between horizontal dipole mode and the distribution of surface sinkholes (Figure 3C). The better correlation may be due to relatively shallower depth of exploration in EM horizontal dipole mode (approximately 7.5 m) than vertical dipole mode of its data collection (approximately 15 m).

The groundwater table is shallow in Basin 2 and limestone bedrock is exposed, partially due to low elevation of the basin (~5 to 6 m lower than the adjacent roads). Surface runoff can directly discharge into groundwater through open sinkholes, providing inefficient management of surface runoff in the basin. To prevent additional sinkhole failure, groundwater level monitoring is needed in the basin since any decline in groundwater levels, either seasonal or uncontrolled abstraction, can reduce the stability of the rock media and lead to further sinkhole failure in the basin (Xeidakis et al., 2004).

Basin 3

No surface karst features were detected in Basin 3. However, fifty-three near-surface GPR anomalies of potential karst features were detected which were categorized as 4 level-A anomalies and 2 level-B anomalies (Table 1, Figure 3, and Figure 4). The most severe anomalies are mainly located in the north part of the basin while the less severe anomalies are located in the south and west of the basin (Figure 3E and 3F). The analysis of EM conductivity contour lines suggests poor correlation between different dipole modes of data collection and poor correlation with GPR anomalies (Figure 3E and 3F). The uncorrelated variations may be due to interference of nearby power supplies. Approximately 10.9 % of survey area in Basin 3 is covered by near-surface features (Table 1). However, no surface sinkholes were observed in the basin. This result may suggest more development of near-surface potential karst features likely due to deep soil depression impacted by deep karst conduits.

Figure 4. Unclassified detected GPR anomalies (yellow color polygons) with the reported sinkhole data (red circle points) within geophysical survey areas (light green color dashed lines) in the Basin 1 (A), Basin 2 (B), and Basin 3 (C).

The detected subsurface features within Basin 3 is in agreement with the GPR survey conducted by Chang et al., (2015). Basin 3 is dry during most of the year and the top soil within the basin consists of sand (Chang et al., 2015). Detected subsurface anomalies explain the dry condition in the basin during most of the year. It is likely for contaminated stormwater runoff to infiltrate into groundwater quickly without sufficient attenuation by top soil. Special consideration is needed for treating contaminated water.

Summary

GPR and EM34-3 geophysical data characterize near-surface karst conditions in three stormwater management basins near Silver Springs, Florida. We find highly heterogeneous conditions with different surface and subsurface configurations below the three stormwater basins, likely due to intrinsic complex and heterogeneous condition of karst system. For instance, interpretation of EM data in karst region of Germany and the Mediterranean came with difficulties due to complexity of its karst system, though the applicability of EM in detecting karst features was noted (Vogelsang, 1987). The effectiveness of GPR in detecting near-surface karst features in this research is in agreement with the obtained results in Florida by Doolittle and Collins (1998). We noted that absence of surficial karst features does not necessarily indicate absence of subsurface features. The combination of different geophysical techniques can improve the level of confidence in interpretation of subsurface feature in complex condition of karst areas. Subsurface heterogeneity within the aquifer can influence contaminant transport and water resources management. Stormwater management in karst areas must be designed to protect groundwater from contaminated surface runoff.

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